FORMATION OF GIANT GASEOUS PROTOPLANETS BY GRAVITATIONAL INSTABILITY. A. P. Boss, DTM, Carnegie Institution of Washington, Washington, DC, 20015-1305, USA, boss@dtm.ciw.edu.

In the process of calculating detailed models of the temperature distribution in the solar nebula, the general trend arose of relatively hot (midplane $T_m \sim 1000$ K) regions inside a few AU, surrounded by relatively cold ($T_m \sim 100$ K) outer regions. Such a situation might permit a "best of both worlds" scenario, where the formation of the terrestrial planets occurred through collisional accumulation of solids in the hot inner nebula, while rapid formation of giant gaseous protoplanets (GGPP) occurred in the cool outer nebula through gravitational instability. The GGPP mechanism avoids the perennial time scale problem associated with making the giant planets through the two step process of collisional accumulation followed by accretion of nebula gas; the time needed to grow the $\sim 10 M_\oplus$ cores needed for the second step may well exceed the lifetime of the gaseous portion of the solar nebula, which can be as short as $\sim 10^5$ years for some solar-type stars.

In addition, the recent discovery of a number of suspected extrasolar planets and brown dwarf stars motivates a re-evaluation of the possible mechanisms for giant planet formation. In particular, the suspected giant planets 47 UMa B, Lalande 21185 B, and 16 Cyg B B have more or less "normal" semimajor axes of several AU or more, but have masses that are factors of 1.5 to 2 times (or more) greater than that of Jupiter. Here a three dimensional (3D) hydrodynamics code is used to study the formation of giant planets through the gravitational instability of a protoplanetary disk.

The GGPP instability depends on self-gravity overwhelming the thermal pressure inside the disk, so the assumed disk thermodynamics is critical. The 3D models all start with a radial temperature profile determined by previous radiative hydrodynamical calculations of the thermal structure of an axisymmetric disk with a mass of $\sim 0.14 M_\odot$ orbiting a solar-mass star. Because radiative transfer is prohibitively slow for these 3D models, we have investigated the effects of thermodynamics by varying the outer disk temperature profile and by varying the effective adiabatic exponent ($p \propto \rho^\gamma$) from $\gamma = 1$ (isothermal) to $\gamma = 7/5$ (adiabatic for molecular hydrogen). These values of γ should span the appropriate range for the solar nebula.

The 3D models show that the outcome of the instability depends more on the minimum value of the Toomre Q stability criterion ($Q < 1$ implies instability) than on the value of γ. The critical value of Q is somewhat greater than 1; disks with Q greater than this will evolve by spiral density waves but will not form GGPP. The GGPP instability can only occur if a means exists for driving Q below the critical value. Clumpy accretion of molecular cloud gas by the disk may be sufficient to drive $Q < 1$ over a short time scale and trigger the GGPP instability in a marginally stable disk.

For isothermal variations, the GGPP instability is damped when the outer disk (T_o) is hotter than about 150 K ($Q_{min} \approx 1.2$). For adiabatic variations with $\gamma = 7/5$, the instability is damped when T_o is hotter than about 100 K ($Q_{min} \approx 1.1$).

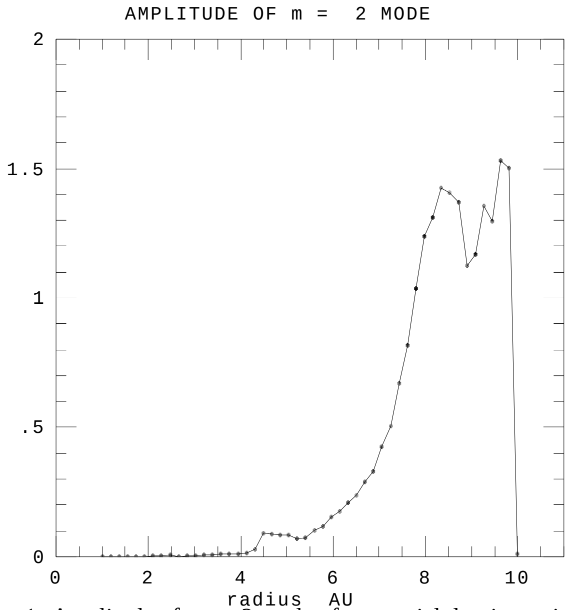
The figures on the next page depict the results of a 3D model with $\gamma = 7/5$ and $T_o = 50$ K, yielding $Q_{min} \sim 0.8$. Growth of nonaxisymmetry in this model initially is slow, with the amplitude of the $m = 2$ mode rising above 0.1 only after 175 yrs, about five rotation periods of the outer disk ($P_o \sim 35$ yrs). By 550 yrs (16 P_o), the dominant $m = 1$ and $m = 2$ modes have grown to amplitudes much greater than 1 (Fig. 1). By this time (Fig. 2), a 7.8 Jupiter-mass clump of gas has formed around 9 AU, as well as a 3.7 Jupiter-mass clump orbiting at 8 AU. Both clumps are gravitationally bound and so should go on to form giant planets.

For a two-arm ($m = 2$) spiral pattern rotating at angular velocity Ω_p, the inner Lindblad resonance (ILR) ($\Omega = m\Omega_p/(m-1)$) occurs at about 5 AU. The ILR demarcates the inner edge of the region penetrated by the spiral arms from the GGPP instability (Fig. 2; see also Fig. 3). The outer Lindblad resonance occurs slightly beyond the edge of the numerical grid and cannot be seen.

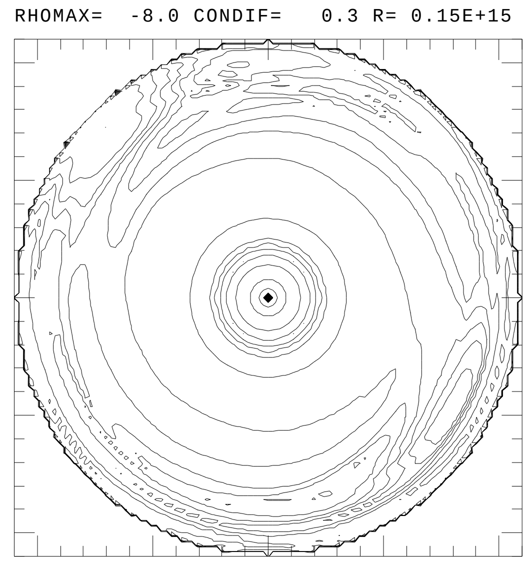
Fig. 4 displays various angular velocities of interest for considering J. A. Wood's (1996) scheme for heating chondrule precursors by passage through a spiral arm shock front. The spiral pattern rotates largely in solid body rotation, as pointed out by Wood, and the resulting difference in linear velocity between planetesimals on Keplerian orbits and the two-armed spiral pattern can be large, especially inside 5 AU, where it exceeds 5 km s^{-1}. However, because the amplitude of the spiral density perturbation is fairly small inside 5 AU, no shock is to be expected there. Shocks may occur nearer the GGPP, where velocity differences of up to 2 km s^{-1} occur in this model, insufficient however to melt chondrule precursors. Wood's idea remains intriguing but unconfirmed.

The models show that GGPP can form in a moderately massive ($\sim 0.14 M_\odot$) disk even if the perturbations behave adiabatically, i.e., they are unable to cool by radiation during their growth phase.

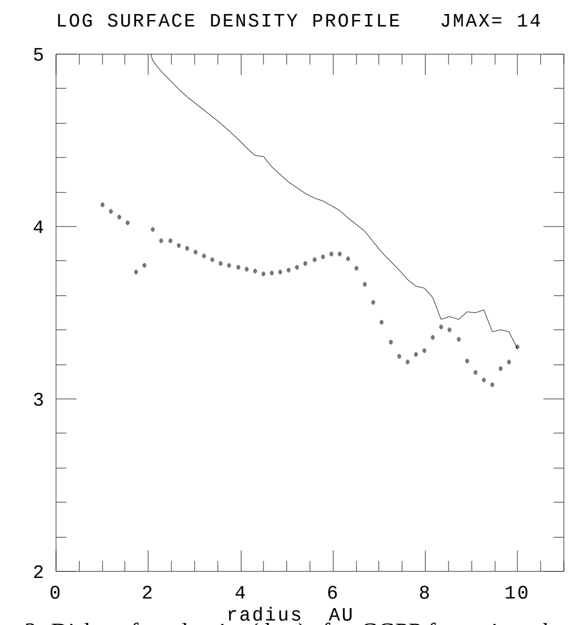
GIANT PLANET FORMATION: A. P. Boss



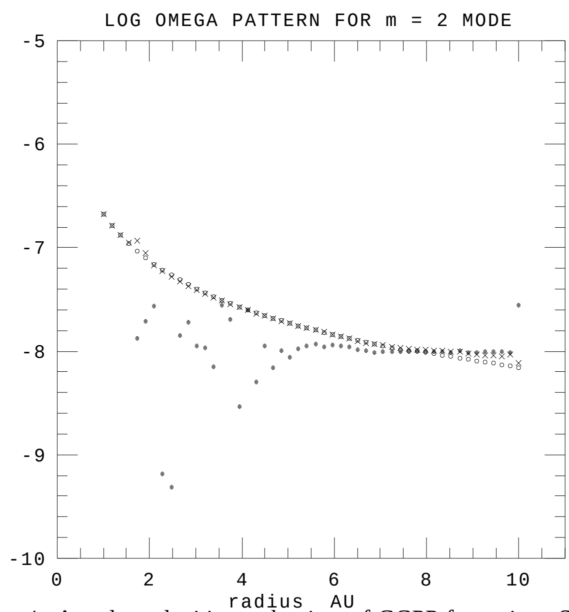
1. Amplitude of $m = 2$ mode of equatorial density at time of GGPP formation. Spiral arms grow in the cool outer disk; the hot inner disk stays axisymmetric.



2. Equatorial density contours (factors of 2) showing formation of two GGPP near edge of 10 AU radius disk (GGPP are at upper left and lower right).



3. Disk surface density (dots) after GGPP formation, showing GGPP hump at 8.5 AU surrounded by “gaps”. Solid line is Toomre’s critical value for instability.



4. Angular velocities at the time of GGPP formation. Solid: pattern speed of $m = 2$ spiral arms. Open: Keplerian (planetesimals). Crosses: fluid (gas).